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DEPARTMENT OF PUBLIC WORKS

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MATERIALS AND RESEARCH DEPARTMENT

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Final Report
M&R 633101
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Mr. J. A. Legarra
State Highway Engineer

Dear Sir:

Submitted herewith is a research report titled:

THE RELATIVE STABILIZING EFFECT

OF VARIOUS LIMES ON CLAYEY SOILS

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Analysis and Report

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Very truly yours,

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REFERENCE: Alexander, M. L., Smith, R. E., and Sherman, G. B., "The Relative Stabilizing Effect of Various Limes on Clayey Soils," March 1971, State of California, Department of Public Works, Division of Highways, Materials and Research Department, Research Report No. 633101.

ABSTRACT: The relative stabilizing effects of two hydrated limes and three quicklimes from various commercial producers are discussed. The effects of variations in lime gradation and calcium hydroxide content on the unconfined compressive strength of three different soils are presented. Correlations are also established between lime gradation and compactability, between specimen density and compressive strength.

KEY WORDS: Lime, soil lime mixtures, stabilization, soil stabilization, compaction, compaction curves, density, moisture content, compressive strength.

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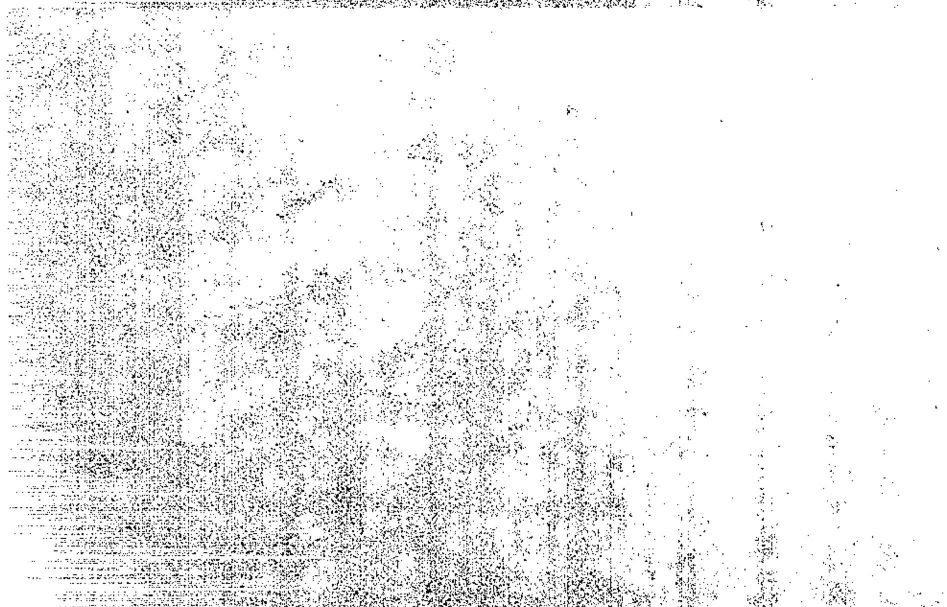

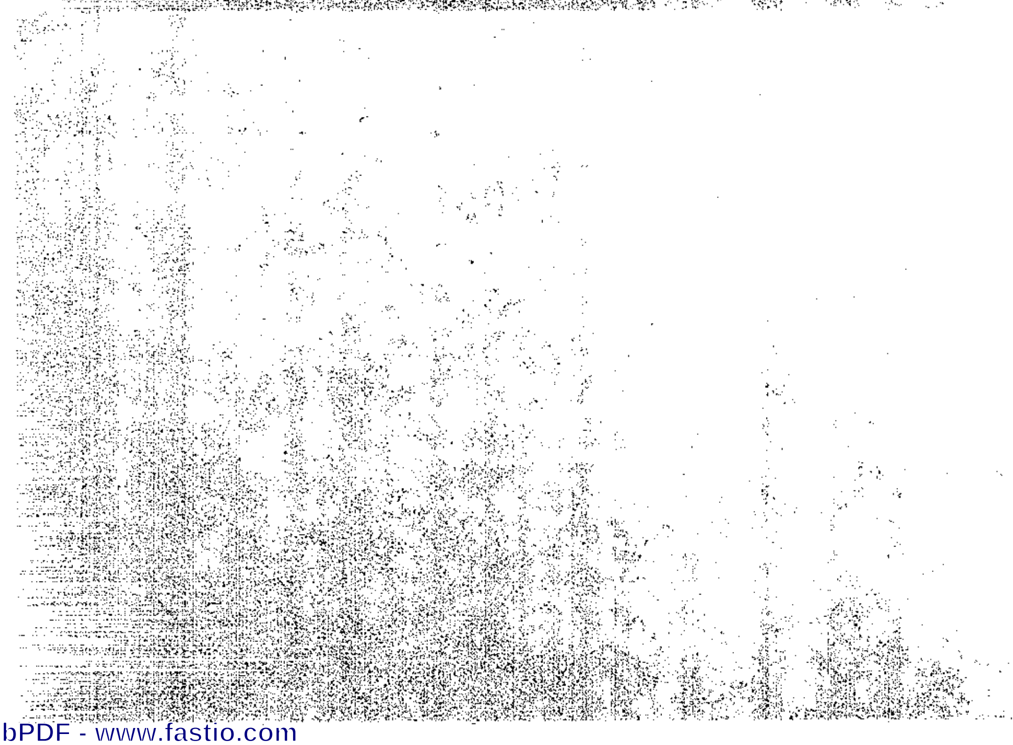

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INTRODUCTION

The use of lime stabilized soil in highway construction has increased rapidly in California during the last decade. Because of increased usage, many advancements have been made in the distribution and mixing equipment. Lime was spread by hand on California's first experimental lime treatment project in 1921. Since that time, various types of distributors, ranging from drag spreader boxes to electronically controlled rotary vane distributors, have been developed and used. Mixing has advanced from "thorough mixing" with discs and harrows to well controlled mixing with high speed rotary mixers. Concurrently, specifications have been developed by the California Division of Highways to control the major phases of the work.

During this advancement period, however, very little change has been made in the requirements on the lime itself. In 1959 California specified a minimum calcium hydroxide content of 85 percent for hydrated lime used in stabilization work. This requirement was reduced to 75 percent in 1961 and then increased again to 85 percent in 1968. The fineness specifications, requiring that not more than 3 percent of the lime be coarser than the #30 sieve and not more than 14 percent coarser than the #200 sieve, were adopted in 1968.

Several lime products, other than finely ground hydrated lime, are commercially available in California today. Although possibly quite effective for soil stabilization, the use of these products is prohibited by the current California Standard Specifications. The objective of this study was to evaluate the relative stabilizing effects of a variety of lime products and to establish a basis for revising existing specifications. The approval of a greater variety of lime products should result in economic savings through increased competition and a more readily available supply of lime.

It is generally accepted that the reaction between a lime and a soil takes place in two distinct phases. The first phase is an immediate reduction in plasticity, presumably the result of a base-exchange and floculation which occurs when the strong calcium cations of the lime replace the weaker metallic ions on the surface of the clay particles. The R-value test, which effectively measures the shear strength of plastic and granular soils, provides a good indication of the effectiveness of this first phase of the reaction.

The second phase of the reaction, however, is a time dependent gain in strength through interparticle cementation. Because the R-value test is not designed to measure strength gain due to cementing, it was decided to compare the relative stabilizing effects of the various limes using an unconfined compressive strength test. One primary advantage of a compression test is the relatively unlimited range in strength which can be measured. The test procedure adopted for the research included the preparation of specimens of treated soil at densities and moisture contents similar to that expected in the field. An accelerated high temperature curing technique was employed. Other researchers (1,2) had indicated that this method would yield strengths in 3 days comparable to that achieved in 3 to 4 months of field curing.

A more detailed description of the testing procedure is included in the discussion.

Soils from three areas of California were treated with varying amounts of five different lime products. These soils represent material from areas where lime treatment has been considered, and the limes represent products available from the three primary producers in California.

CONCLUSIONS AND RECOMMENDATIONS

1. Quicklime was found to be generally more effective than hydrated lime for improving the compressive strength of soils, when compared on an equal percentage by weight basis. The primary reason is the greater calcium hydroxide protential of quicklime. The quicklimes included in this study had an equivilence of approximately 50 percent more calcium hydroxide than that represented by the same weight of the hydrated limes.

It is recommended that the California Standard Specifications be revised to permit the use of quicklime for soil stabilization.

2. A fineness of hydrated lime of more than 75 percent passing the #200 sieve does not appear to increase its effectiveness in soil stabilization. It is, therefore, recommended that the fineness requirements for hydrated lime be revised to allow up to 25 percent to be retained on a #200 sieve.

In conjunction with this suggested change in fineness requirements, it is also recommended that an arbitrary wash sieving time of 15 minutes be required for all hydrated lime samples. This last recommendation is due to the fact that the apparent amount of lime finer than a #200 sieve is dependent on wash sieving time. (AASHO Designation T219-66 I leaves the actual washing time entirely to operator judgement.)

3. At lime contents above 2 percent, higher compressive strengths are obtained with the coarser quicklime products than with those ground excessively fine. This is apparently due to the effect the fine limes have of reducing the compactibility of the treated soil. The resulting lower densities of test specimens, and lesser strength, offset the benefits which would otherwise be expected from use of the finer limes.

It is recommended that the specifications be written to allow the use of quicklime in a crushed or granular form.

4. A loose curing period for soils treated with quicklime is required to prevent expansion and pop-outs caused by hydration of the lime. A 24 hour period is satisfactory.

5. There is approximately a 6 percent difference in the optimum moisture contents determined by the California impact test (Test Method No. Calif. 216) and the kneading compactor. Since the kneading compactor closely duplicates normal field compaction, it is concluded that optimum field moisture contents may be estimated from moisture-density curves determined with the California kneading compactor.

6. Slippage or compaction planes are easily formed in lime treated soils. Consequently, it is desirable that the material be compacted in layers of maximum thickness, providing that the desired density is obtained.

DISCUSSION

Background

Lime treatment has been used by the California Division of Highways since the late 1940's as a means of improving the quality of base and subbase materials. A wide variety of soil and aggregate types, ranging from heavy clays to decomposed granite, and aggregates contaminated with plastic fines, have been lime treated with apparent success for use in the structural section.

Beginning with an experimental project in 1964, California has also used lime to treat expansive soils under major freeways paved with portland cement concrete. Because the California design procedure takes into account the potential expansion of basement soils, structural sections up to four feet thick are often required due to this factor. Lime treatment of the upper portion of the expansive basement soils, however, has made it possible in these instances to substantially reduce structural section thicknesses. Treatment with lime not only eliminates the expansion potential of the treated material, but is also considered to create a moisture barrier to underlying untreated soils.

As a result of these successful applications of lime in California highway construction, the use of lime increased rapidly during the middle and late 1960's. Since 1967 more than 225 lane miles of california highways have included lime treated materials.

Some of the early stabilization was attempted with hydrated "agricultural" lime or waste lime by-products from some other manufacturing process. There was very little control on the quality of lime during the initial stages of development of lime stabilization, but as knowledge and experience increased, the need for such provisions became evident.

The first specific control over the quality of lime used by the State of California was a requirement for the calcium hydroxide content. Beginning in 1959 a minimum calcium hydroxide content of 85 percent was specified in the Special Provisions for lime treatment projects under the control of the California Division of Highways. In 1961 the calcium hydroxide requirement was reduced to 75 percent to take advantage of what appeared to be potential cost savings from the use of lower grade limestone.

As the use of lime increased, the manufacturing processes and/or materials sources improved, and in 1968 the calcium hydroxide content requirement was again set at 85 percent minimum in accordance with proposed requirements for Type I, Grade B lime set forth in AASHO Designation M216-68I. At the same time the fineness requirements that not more than 3 percent be retained on the No. 30 sieve and not more than 14 percent be retained on the No. 200 sieve, were also adopted from the proposed AASHO specifications.

The requirements for lime treatment were first included in the California Standard Specifications in 1969, and described the use of a commercial, dry, hydrated lime conforming to the calcium hydroxide and fineness requirements noted above. These requirements remain unchanged in the current 1971 Standard Specifications. Quicklime is not included as a stabilizing agent in these standards.

Both hydrated lime and quicklime which do not meet the present California grading requirements are commercially available. Some of these, however, have been used with apparent success by a few counties within California.

As a consequence, it was decided to reevaluate the relative stabilizing capacities of various limes on clayey soils. The effects of lime gradation, and the comparison of quicklime with hydrated lime were to be the main objects of the study. It was proposed that representative clayey soils be treated with varying amounts of the limes. The treated soils were to undergo an accelerated curing period prior to determining their unconfined compressive strengths.

Materials

Three soils, representing areas within the Sacramento and San Joaquin Valleys where extensive lime stabilization work has been done, or is being planned, were selected for this study. One soil, which will be referred to as Soil No. 1 throughout the remainder of the discussion, was obtained from the southwest portion of Tulare County along Route 43 south of Corcoran. The second soil, Soil No. 2, was obtained from the embankment material used on Interstate Route 5 through the City of Stockton. The third soil, Soil No. 3, was obtained from the vicinity of the Sacramento Metropolitan Airport where extensive lime stabilization work has been done on Interstate Routes 5 and 880.

Laboratory quality and identification tests were performed on each of the untreated soils. These tests (3) included mechanical analysis, resistance (R-value) by the stabilometer, resistance (R-value) by expansion pressure, sand equivalent value, plasticity index and classification of the mineral content of each by x-ray diffraction and differential thermal analysis. The results of these tests are presented for comparison in Table 1.

The three soils were very similar in some of their physical properties. The plasticity index was nearly identical for all three; however, both the liquid limit and the plastic limit were somewhat higher for Soil No. 3 than for Soils No. 1 and No. 2.

Based on the low sand equivalent test values, each of the materials had a high concentration of clay sized particles. The sieve analyses showed that Soil No. 1 had a relatively higher proportion of sand, as determined by the amount of material retained on the #200 sieve. Soil No. 3 had a greater proportion of clay sized material as determined by the amount of material smaller than the 5 micron size. Soil No. 2 was more or less in the middle in regard to particle size distribution.

There were only relatively small differences between the soils when comparing the resistance (R-value) by the stabilometer method, but when compared by resistance (R-value) by expansion pressure there were large differences. The R-value by stabilometer is a measure of a material's capacity to support a load, without lateral deformation, while in a saturated condition. The R-value by expansion, on the other hand, is a measure of the expansion pressures which can develop as a compacted material is subjected to additional water. The 84 R-value by expansion, recorded for Soil No. 1, indicates that this material has very little potential for expansion. The expansion R-value of 12 on sample No. 3 shows that this material could produce high expansion pressures.

Five limes were obtained from the three major lime producers in California. Two of these were hydrated limes representing that currently being used in construction on California highways. The other three were quicklimes representing various types of quicklime which are commercially available. Sieve analyses were determined for the limes and are listed in Table 2.

Table 1

SOIL DATA

	Soil No. 1	Soil No. 2	Soil No. 3
Partical Size			
% passing #4 sieve	99	96	98
" #30 "	98	95	96
" #50 "	97	94	95
" #100 "	90	91	95
" #200 "	75	85	94
5μ (hydrometer)	42	46	60
1μ "	23	28	28
R-value by Exudation	13	23	20
R-value by Expansion	84	34	12
Sand Equivalent	2	2	4
Liquid Limit	38	39	49
Plastic Limit	20	19	30
Plasticity Index	18	20	19
Minerals Present (percent)*			
Quartz	20-25	25	25
Feldspar	15-20	20-25	10-15
Montmorillonite	15-20	10	10-15
Chlorite	<5	5	15
Organic	5	5	5-10
Iron Oxide			5-10
Iron	5		
Amorphous			10
Mica	<5		5
Biotile		5-10	
Hornblende		5	
Geothite	5	5	
Halloysite		5	
Calcite	5		
Amphibole	<5		
Asbestos	1-2		
Others	5	5	5

*Estimated on the basis of x-ray diffraction and DTA data.

Table 2

PARTICLE SIZE ANALYSIS

Percent Passing	Hydrated Lime		Quicklime		
(Sieve)	A	B	C	D	E
#4					100
#8			100		95
#16			83		82
#30	99	98	49	100	62
#50			12	99	43
#100			3	90	28
#200	92	76	1	34	12

The sieve analyses of the hydrated limes were determined in accordance with AASHO Designation T219-66I. This test procedure requires washing a representative portion of the lime over the #30 and #200 sieves until the water passing through the sieve is clear. Ten to twelve minutes of washing was required to achieve this end point for each of the two hydrated limes. The data listed in Table 2 show that there is a measurable difference in the fineness of the two hydrated limes. Hydrated Lime A, with 92 percent passing the #200 sieve, meets the current grading requirements while Hydrated Lime B, with only 76 percent passing the #200 sieve, does not.

It should be pointed out, however, that not all organizations involved in the processing and testing of lime are in agreement in the interpretation of the end point of this test. In addition to requiring that the washing continue until the water passing through the sieve is clear, the AASHO procedure further states that if milkiness persists, the washing operation may be continued up to a maximum of 30 minutes. This has been interpreted by some to mean that any particles visible in the clear water authorizes additional washing. This interpretation greatly increases the washing effort and decreases the amount of coarse particles retained on the sieves. When these two limes were washed for the full 30 minutes the amount of material passing the #200 sieve was increased to 97 and 92 percent, respectively, for Limes A and B.

The sieve analyses of the quicklimes were determined by dry sieving. Two-hundred gram samples were sieved through nested eight inch diameter screens using a mechanical sieve shaker and a ten minute shaking time.

The particle size distributions, determined for the three quicklimes, were totally different from one another. These differences were due to the manufacturing processes used by the various lime producers and consequently a product supplied by one producer is not necessarily reproducible by others. Quicklime C, referred to in this report as a granular quicklime, has a sizing and texture attributed to the properties of the particular limerock, as well as the processing used by the producer. Quicklime D was pulverized as a part of the manufacturing process in order to produce a finely ground product. Quicklime E was an unfinished product in that it was obtained from the processing plant before being subjected to final pulverization.

Calcium hydroxide contents, $Ca(OH)_2$, were determined for each lime using Test Method No. Calif. 414. This California method is a modification of ASTM Designation: C 25. Calcium oxide, CaO, equivalents were determined from the calcium hydroxide contents by using a conversion ratio of 1.32:1.00 which is in accordance with definitions in ASTM Designation: C 25. Both the calcium hydroxide and calcium oxide contents indicate the amount of lime available for reaction in the treatment of a soil. The percentages of $Ca(OH)_2$ and CaO, shown in Table 3, are relative based on initial equal amounts of lime, by weight.

Table 3

APPROXIMATE CHEMICAL ANALYSIS
(percent by weight)

Properties	Hydrated Lime		Quicklime		
	A	B	C	D	E
CaO	65	64	95	93	93
$Ca(OH)_2$	86	85	125*	123*	123*

*Percent $Ca(OH)_2$ after hydration of quicklime.

Testing

The objective of the testing program was to provide data for comparing the relative stabilizing capacities of the various limes on different soils.

The following mixing and compacting procedures were adopted in order to prepare the test specimens in such a manner that their condition would correspond to materials treated and placed under normal field conditions. The California kneading compactor, as used in Test Method No. Calif. 301, was used for laboratory compaction since the compactive action and the resulting densities are similar to that achieved during highway construction.

The soils were dried and processed until all material, other than rock, passed the #4 sieve.

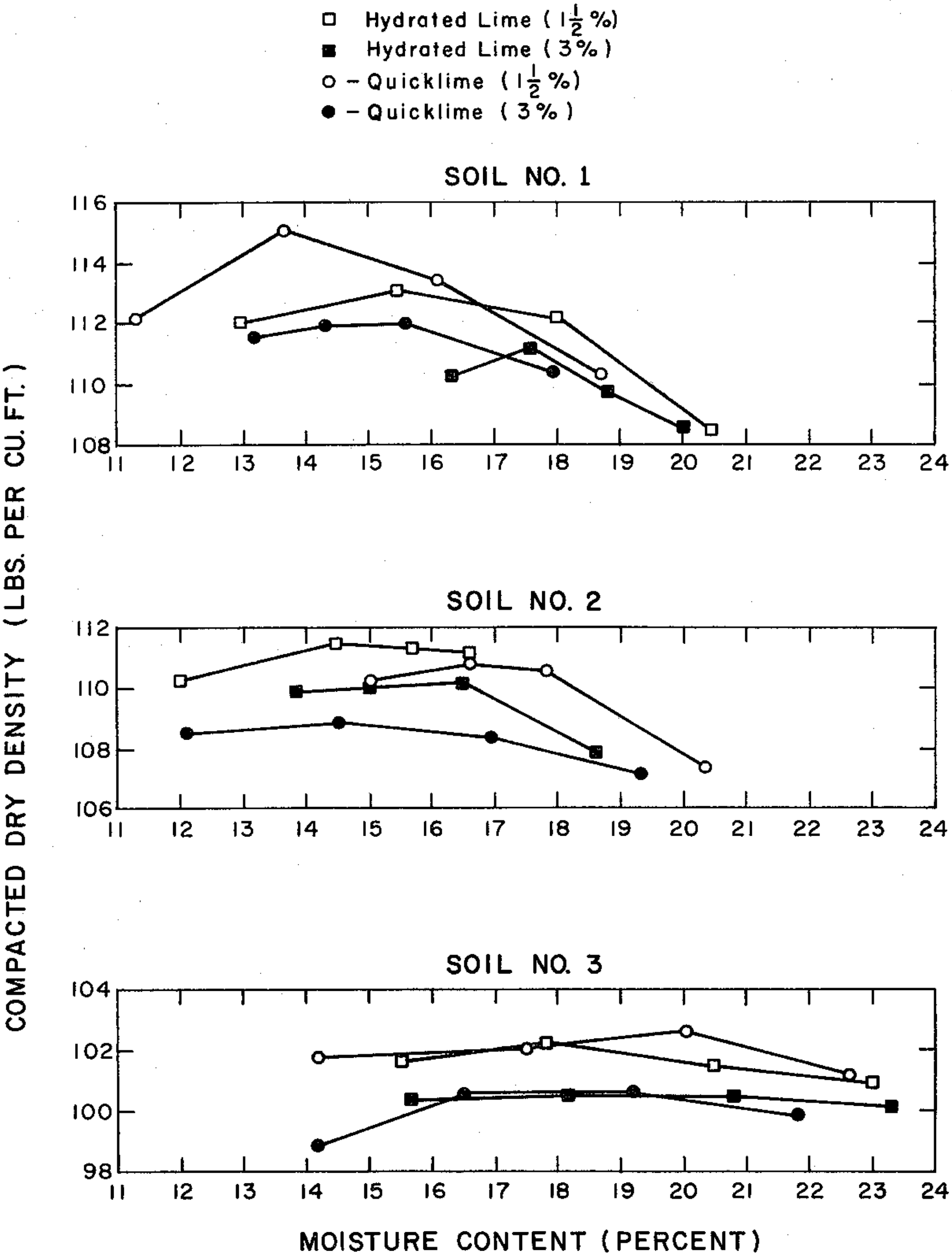
Measured amounts, by weight, of the soil, lime and water were thoroughly blended together using a mixing bowl, trowel and water metering burette. The soil and lime were combined first to aid in distribution of the lime and then the entire predetermined volume of water was blended in. Care was taken during mixing to avoid crushing or breaking up lumps of lime which would normally not be broken up by construction procedures.

The amount of water added to the test specimens was predetermined on the basis of moisture-density curves established in accordance with Test Method No. Calif. 216. Separate curves were established for each soil when treated with hydrated lime and quicklime because of the difference in water demands between the two types of lime. These moisture-density determinations are plotted in Figure 1.

Figure 1

MOISTURE - DENSITY CURVES

(LIME TREATED SOILS)



The curves indicate that in most cases small variations in moisture content are not critical to the density of the compacted material. With some soil-lime combinations, the moisture content varied by as much as 8 percent without changing the compacted dry density by more than one pound per cubic foot. This broad range made it possible to select a single moisture content which could be used for a given soil even though the amount of lime varied.

After blending the soil, lime and water, the mixture was placed in an airtight container and allowed to loose cure for approximately 24 hours. This time corresponds to a practical minimum field curing period for most projects.

Following the loose curing period, the mixture was compacted into 4 inch diameter by 4 inch high tin liners using the kneading compactor. Compaction was applied at a foot pressure of 250 psi as the material was placed in the mold in 20 equal increments, and then continued for 100 load applications at a foot pressure of 350 psi after all of the material was introduced. A final static pressure of 350 psi was applied over the surface area to level and smooth the surface. This compactive procedure resulted in densities equal to approximately 95 percent of the maximum density obtain by Test Method No. Calif. 216.

Curing of the compacted test specimens was accomplished in two phases. With the compacted specimens still in the tin liners, the ends were capped and sealed with tape and then placed in a 110°F oven for seven days. A review of work by other researchers (1,2) indicated that increased curing temperatures would provide, in a few days, the same strengths that would be gained after several months under field conditions. Based on available data it was estimated that the seven day curing at 110°F would be approximately equal to three months in the road. Roadway structural sections, however, are normally subject to saturation after a period of time. To compensate for this normal exposure to water the curing cycle was completed by removing the tin liners and burying the specimens in a confined, saturated sand for 21 days.

Following the curing phase the ends of the specimens were capped with plaster of paris to provide a smooth bearing surface and then loaded to failure in the compression testing machine. The compressive load was applied at the rate of 0.05 inch per minute.

Data Evaluation

The data accumulated from the described testing program are recorded in Table 4. The values shown for dry density and unconfined compressive strength are the averages of replicate test specimens. In most cases it is the average of three tests, but because of an insufficient quantity of Soil No. 2, the values shown for Soil No. 2

Table 4

EFFECT OF LIME

	Soil #1				Soil #2				Soil #3			
Lime*	(1) % Lime	(2) % H_2O	Dry Density lbs/cu.ft.	Unconfined Compressive Strength-psi	(1) % Lime	(2) % H_2O	Dry Density lbs/cu.ft.	Unconfined Compressive Strength-psi	(1) % Lime	(2) % H_2O	Dry Density lbs/cu.ft.	Unconfined Compressive Strength-psi
H-A	1	16.5	109	95	1	16.6	106	30	1	19.9	99	32
H-A	2	16.3	106	312	2	16.5	103	87	2	19.7	96	102
H-A	3	16.1	105	507	3	16.4	101	120	3	19.6	95	131
H-A	4	16.0	105	497	4	16.3	101	128	4	19.4	94	118
H-B	1	16.5	110	126	1	16.6	105	23	1	19.9	99	37
H-B	2	16.3	107	360	2	16.5	102	79	2	19.7	96	114
H-B	3	16.1	105	508	3	16.4	101	100	3	19.6	95	131
H-B	4	16.0	103	450	4	16.3	100	117	4	19.4	94	118
Q-C	1	18.2	111	233	1	17.6	108	94	1	20.0	99	60
Q-C	2	18.1	110	458	2	17.5	105	222	2	19.8	98	181
Q-C	3	17.9	109	531	3	17.3	102	227	3	19.6	96	194
Q-C	4	17.8	106	486	4	17.2	100	219	4	19.5	93	177
Q-D	1	18.2	109	181	1	16.7	106	65	1	20.0	97	54
Q-D	2	18.1	104	504	2	16.6	102	122	2	19.8	94	122
Q-D	3	17.9	101	480	3	16.5	100	159	3	19.6	94	114
Q-D	4	17.8	102	425	4	16.4	99	178	4	19.5	92	113
Q-E	1	18.2	111	142	1	---	---	---	1	20.0	99	59
Q-E	2	18.1	107	477	2	15.8	104	165	2	19.8	96	157
Q-E	3	17.9	103	514	3	17.3	101	175	3	19.6	94	157
Q-E	4	17.8	101	463	4	17.2	99	178	4	19.5	92	137

*H-A Hydrated Lime A (fine)
H-B Hydrated Lime B (fine)
Q-C Quicklime C (Granular)
Q-D Quicklime D (Fine)
Q-E Quicklime E (Not Pulverized)

(1) Percent lime is based on dry weight of soil.
(2) Percent moisture is based on dry weight of soil and lime.

when treated with Quicklime D represent single test values. To simplify the presentation of the test results, the compressive strengths are plotted against the respective lime contents in Figure 2. Several basic relationships were observed from this plotted data and are considered in the following discussion.

A considerable difference in the effect that lime has on various soils was immediately obvious. Soil No. 1 gained unconfined compressive strengths in excess of 500 pounds per square inch while soils No. 2 and No. 3 attained maximum strengths of 230 and 190 psi, respectively. Although these differences are noted it was not within the scope of this study to determine the factors responsible.

Aside from the large difference in maximum strengths, there were also distinct differences in the pattern of strength gain in relation to the amount and type of lime used for stabilization.

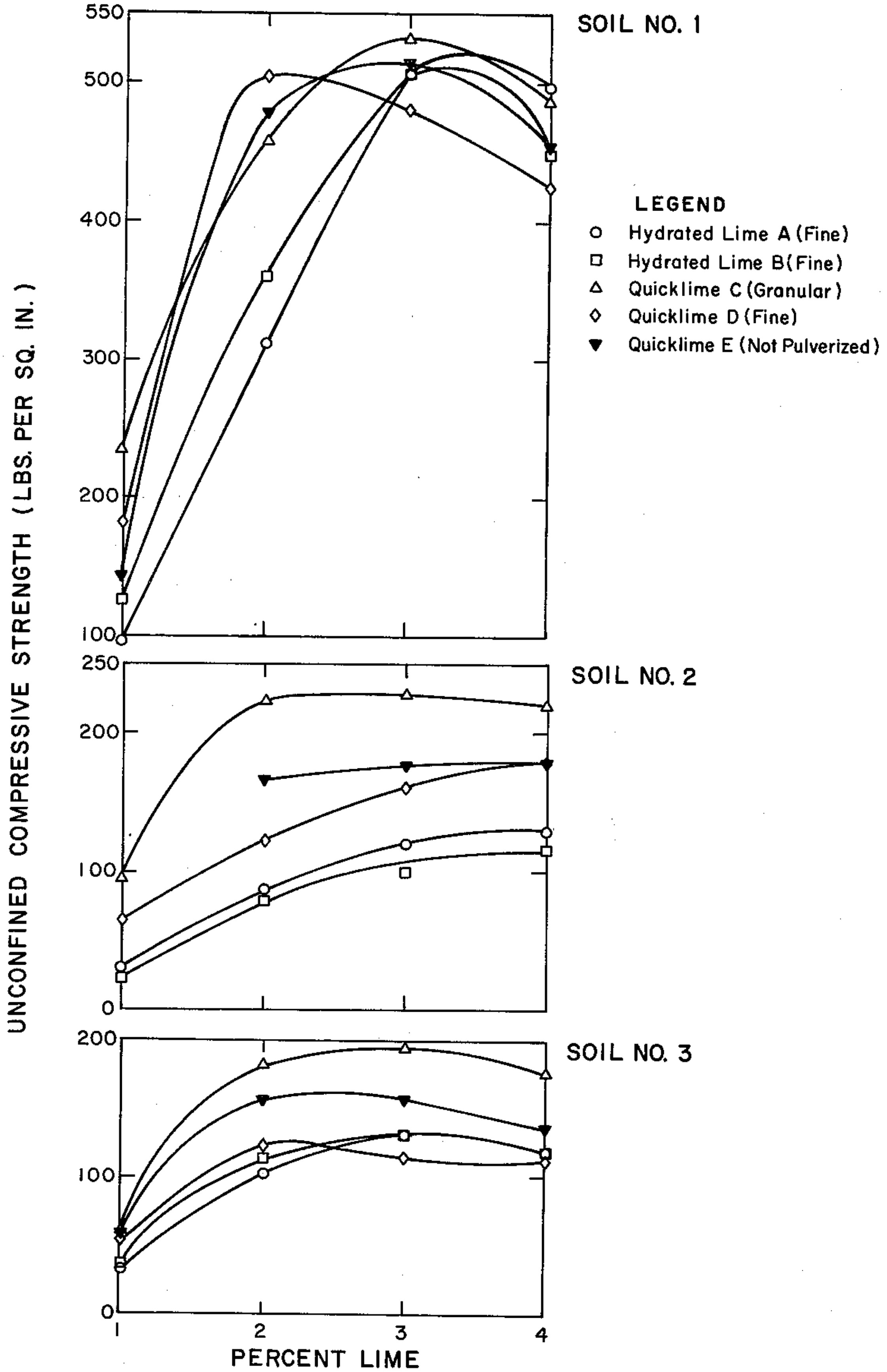
One phenomenon made evident by the plotted data was the reduction in strength as the lime content was increased above an optimum amount. This was particularly evident in tests on Soil No. 1. Evidence will be presented later which indicates that this may be primarily due to decreases in the compacted dry density of the test specimens. However, it is acknowledged that the apparent optimum lime content increases with longer curing periods before testing (4).

The compressive strength tests indicated only insignificant differences in the stabilizing effects of the two hydrated limes. The principal difference observed in characteristics between Hydrated Limes A and B was the amount passing the #200 sieve. As shown in Table 2, 92 percent of Hydrated Lime A passed the #200 sieve while 76 percent of Hydrated Lime B passed the #200 sieve. Since no significant difference in stabilizing effect accompanied these variations in grading, it was concluded that the present grading requirements are more restrictive than necessary.

In general, each of the quicklimes was more effective than the hydrated limes when compared on an equal weight basis. Soil No. 1 ultimately reached approximately the same maximum strength with each of the five limes; however, 3 percent of the hydrated limes was required to achieve the same maximum strength achieved with 2 percent of the quicklimes. Soils No. 2 and No. 3 never gained the same maximum strengths with hydrated lime as were with quicklime. On the other hand, there was considerably more variation in compressive strengths between soil specimens treated with the different quicklimes than was found using the two hydrated limes.

Figure 2

PERCENT LIME VS COMPRESSIVE STRENGTH



The most apparent reason for the difference in compressive strengths between test specimens treated with quicklime and those treated with hydrated lime, was the higher proportions of calcium hydroxide available from the quicklime. As shown in Table 3 each of the quicklimes contained nearly 50 percent more calcium hydroxide than an equal amount, by weight, of the hydrated limes. In order to compare the two types of lime on an equal basis the calcium hydroxide content of the test specimens was calculated as a percentage of the dry weight of the soil sample. This was done by multiplying the calcium hydroxide content of the lime by the percent of lime which had been added to the soil.

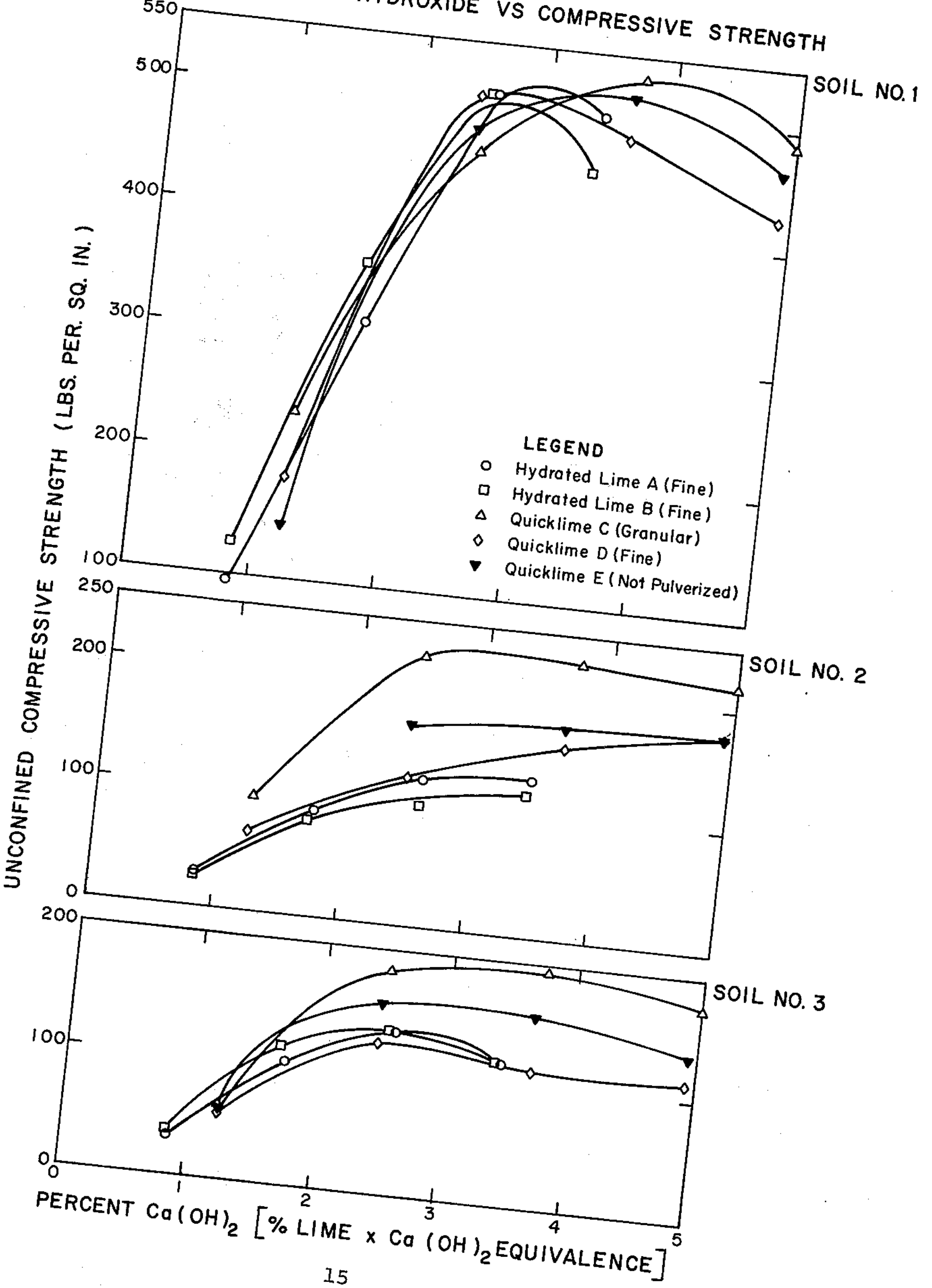
The compressive strengths versus lime contents data were replotted in Figure 3 on the basis of final $Ca(OH)_2$ content. When plotted in this way much better correlation was found between specimens of Soil No. 1 treated with the different limes. This data now shows that this soil responded comparably with each of the limes. Both the maximum strength and the rate of strength increase, as related to lime content, were essentially the same regardless of the lime used.

Figure 3 also shows an improved correlation in test results between the finely ground Quicklime D and the hydrated limes for both Soils No. 2 and No. 3. There was still, however, a considerable difference in strengths when the coarser quicklimes were used. Obviously the amount of available calcium hydroxide is not the only factor affecting the unconfined compressive strength of the treated soil.

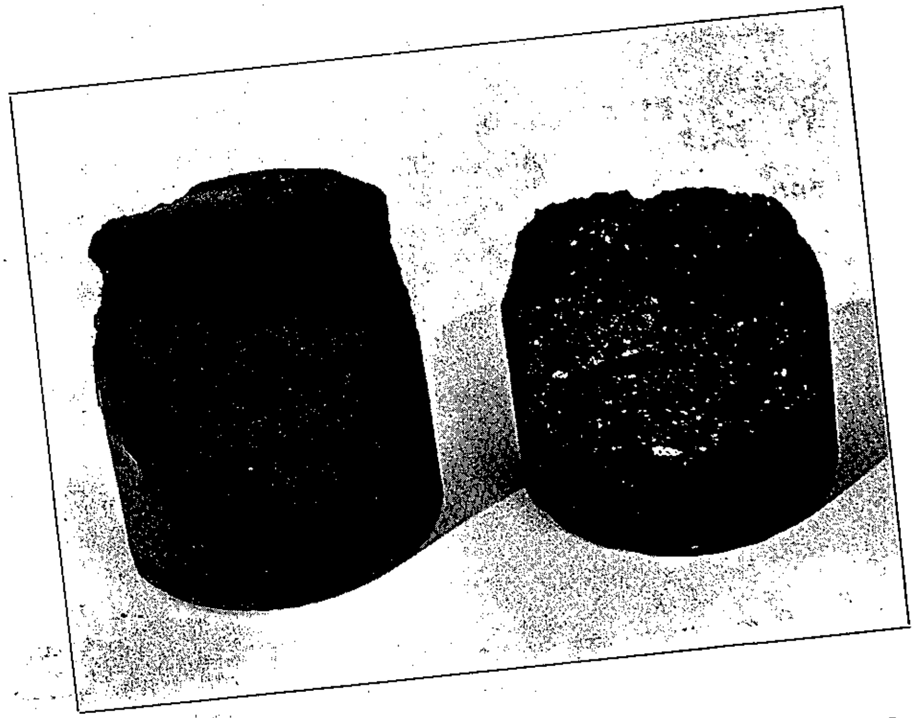
The broken test specimens shown in Photograph No. 1 tend to indicate that the finer lime particles can be more evenly distributed throughout the soil than the granular particles. Theoretically this should, in turn, result in higher strengths. The compressive strength test results, however, do not support this theory. The compressive strength of Soil No. 2, for example, was 80 percent higher when treated with 2 percent of the granular Quicklime C than when treated with an equal amount of Quicklime D. Although the variations were not as great with the other soil-lime combinations, the compressive strengths achieved with Quicklime C were almost always higher than with either of the other quicklimes. At the same time the lowest strengths recorded for each concentration of quicklime were generally found with specimens treated with the finely ground Quicklime D.

Figure 3

PERCENT CALCIUM HYDROXIDE VS COMPRESSIVE STRENGTH



Photograph No. 1



Distribution of Fine and Coarse Lime Particles

The possible cause of these strength variations appeared to be related to the relative density of the compacted test specimens. Past experience with cement treated aggregates has shown that compressive strength is directly associated with the compacted density of the treated material. Therefore, it is informative to study the effect of the different limes on density, and the correlation with compressive strength.

A review of the data in Table 4 showed that both the amount of lime and the type of lime affected the density of the compacted specimens.

In every instance the densities of the compacted test specimens decreased as the amount of lime increased. This decrease in density averaged about 2 lbs./cu. ft. with each 1 percent increase in lime content. The density of Soil No. 1 varied from 111 lb./cu. ft. to 101 lbs./cu. ft. when treated with 1 and 4 percents of Quicklime E.

However, if the lime content is held constant it is found that the different limes also caused variations in densities of as much as 8 lb./cu. ft. The general trend was for the specimens treated with the granular quicklime to have the highest densities, while specimens treated with the finely ground quicklime had the lowest densities. The largest variation was observed when Soil No. 1 was treated with 3 percent lime. In this instance the density of specimens treated with the granular Quicklime C was 109 lb./cu. ft., while duplicate specimens treated with the finely ground Quicklime D had a density of 101 lb./cu. ft.

Because of the differences in calcium hydroxide contents it was a little more difficult to compare quicklime and hydrated lime with regard to fineness. However, since 3 percent hydrated lime contained approximately the same amount of calcium hydroxide as 2 percent quicklime, a comparison was made with these concentrations.

In Figure 4, the test specimen densities are plotted against the percent of the lime which passed the No. 30 sieve. When plotted in this way there is a definite correlation between density of the compacted material and fineness of the lime. The type of lime makes no apparent difference when equal concentrations of calcium hydroxide are compared.

To correlate the effect that this variation in density had on compressive strength, the test data for Soils No. 2 and No. 3, when treated with 2 percent quicklime and 3 percent hydrated lime, were plotted in Figure 5. Soil No. 1 was not included because of the similarities in compressive strength regardless of the lime used.

To test the hypothesis that the fineness of the lime can account for these variations, an experiment was prepared using coarse and fine lime from the same source. This was accomplished by thoroughly pulverizing a portion of the granular Quicklime C and then treating duplicate specimens with equal amounts of the pulverized and granular quicklime. A soil similar to Soil No. 3 was used in this series of tests. Both the densities and compressive strengths of these specimens are recorded in Table 5.

Table 5

GRANULAR VS. PULVERIZED QUICKLIME

Percent Lime	Lime C (Granular)		Lime C (Pulverized)	
	Avg. Density lb./cu.ft.	Avg. Strength lb./sq.in.	Avg. Density lb./cu.ft.	Avg. Strength lb./sq.in.
1	97	47	95	55
2	94	105	93	122
3	93	150	90	129
4	91	155	88	120

Figure 4

COMPACTED DENSITY OF TREATED SOIL VS FINENESS OF LIME

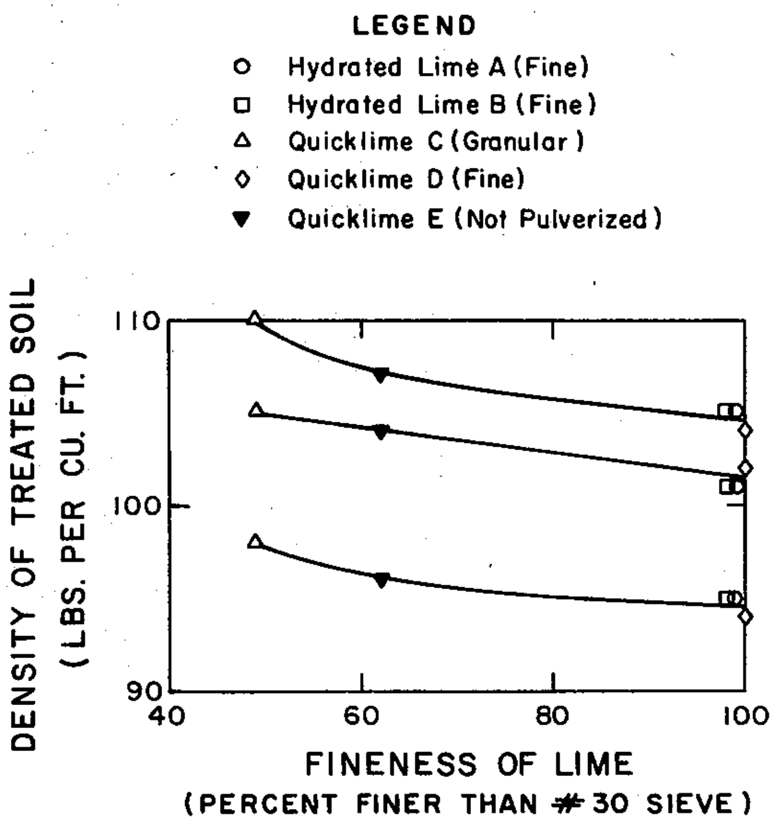
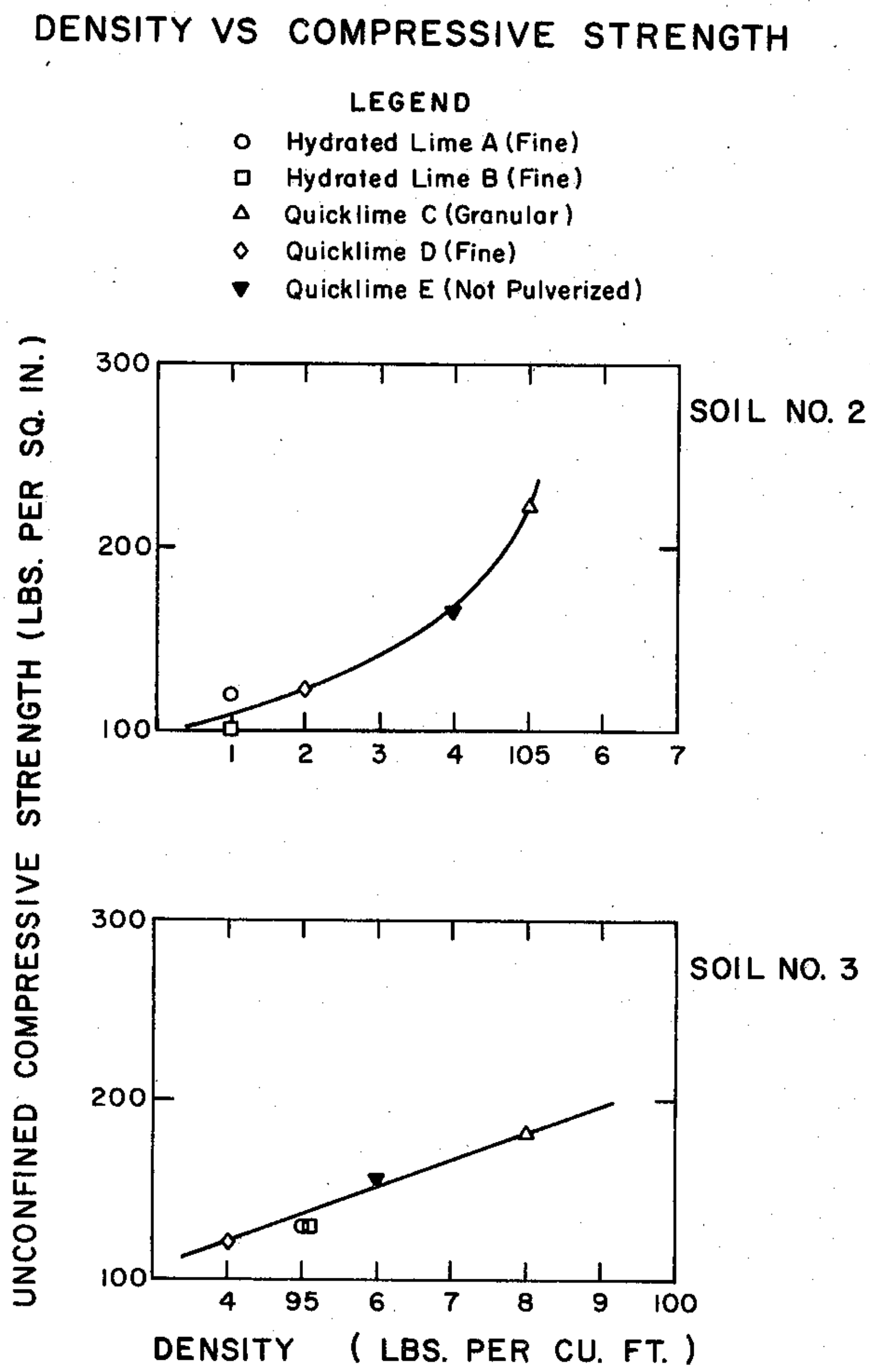


Figure 5


DENSITY VS COMPRESSIVE STRENGTH
LEGEND
Hydrated Lime A (Fine)
Hydrated Lime B (Fine)
Quicklime C (Granular)
Quicklime D (Fine)
Quicklime E (Not Pulverized)
UNCONFINED COMPRESSIVE STRENGTH (LBS. PER SQ. IN.)
300
200
100
1
2
3
4
105
6
7
SOIL NO. 2
300
200
100
4
95
6
7
8
9
100
SOIL NO. 3
DENSITY (LBS. PER CU. FT.)

The densities of the specimens treated with the pulverized quicklime ranged from 1 to 3 lbs./cu. ft. lower than those treated with the granular quicklime. Also, for percentages of lime greater than 2 percent, the compressive strengths of specimens treated with the pulverized quicklime were less than those of the granular quicklime. Since the lime contents specified for California highway projects are typically 2 to 4 percent, it is concluded that the coarser quicklime would be more effective in the field than the finely ground.

The question still existed as to whether a difference in water demand between the coarse and fine quicklimes could cause the differences in density which were observed. To provide an answer, duplicate sets of soil specimens were treated with 3 percent of granular quicklime, and the same quicklime in a pulverized condition. The specimens were then compacted in the kneading compactor with varying amounts of water. The moisture-density curves shown in Figure 6 were obtained from the data. The optimum moisture range for soil treated with the pulverized quicklime is somewhat broader, but the maximum density obtained was 2 lbs./cu. ft. less than that of the soil treated with the coarse or granular quicklime.

To summarize, it has been established that the fineness of lime affects the compactibility of a treated soil. At percentages of lime above 2 percent, the resulting reduction in density from use of the finer limes causes a strength loss which is greater than the benefits which would otherwise be expected from use of the finely ground products.

Related Findings

In addition to comparing the relative stabilizing effects of the various lime products, several other important points related to the mixing and compacting of lime treated soil were brought to light during the course of this study.

Compacted specimens of untreated Soil No. 3 were subjected to the same curing procedures as the treated soils. These untreated specimens increased in height by 0.4 inch during the curing phase of the test. The lime treated specimens of the same soil had only minor increases in height due to expansion. The average expansion of 3 replicas each of treated and untreated specimens of Soil No. 3 are listed in Table 6. For treated specimens the greatest expansion measured was 0.13 inch when 1 percent hydrated lime was used. Lime contents of 2 percent or more reduced the expansion to .03 inch or less.

Figure 6

EFFECT OF LIME FINENESS ON MOISTURE - DENSITY CURVES

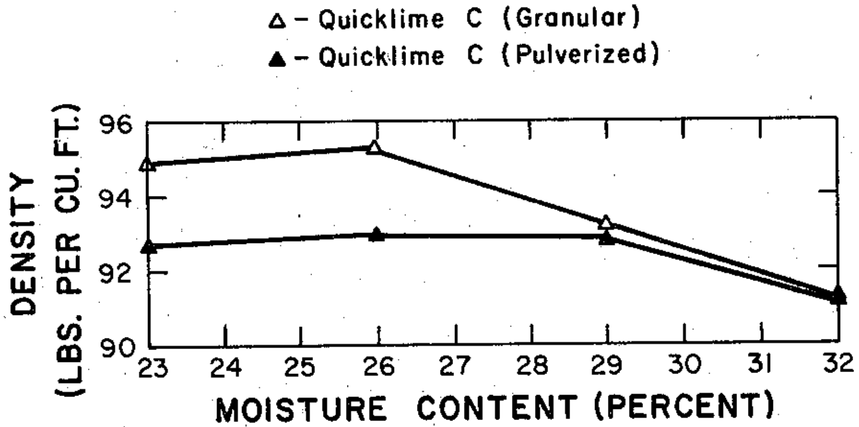


Table 6

AVERAGE EXPANSION OF TEST SPECIMENS
(Soil No. 3, three replicas each)

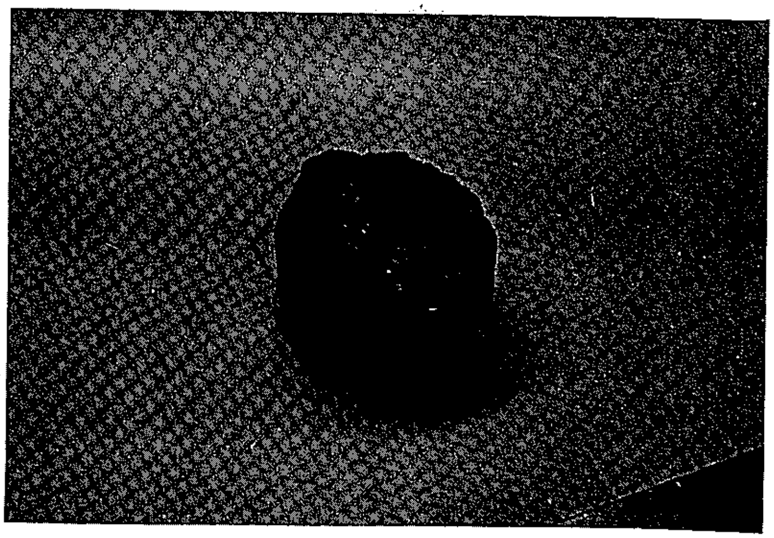
Percent Lime	Lime A	B	C	D	E
0	0.40"	0.40"	0.40"	0.40"	0.40"
1	0.13	0.10	0.07	0.06	0.07
2	0.03	0.02	0.03	0.03	0.02
3	0.02	0.02	0.02	0.02	0.02
4	0.02	0.02	0.03	0.02	0.01

Data from tests on Soils No. 1 and No. 2 also indicated negligible expansion when stabilized with lime. It can be concluded that under these test conditions, treatment with lime will greatly reduce, or eliminate, expansion of some compacted soils.

It was also found that the lime may cause expansion of the compacted soil under certain conditions. A series of test specimens, treated with the granular Quicklime C, was compacted immediately after preparation, that is, without the 24 hour loose curing period. Excessive expansion and pop-outs on the surface of the specimens became evident almost immediately after compaction. This phenomenon was apparently the result of expansion of the quicklime particles as they reacted with water during the hydration process. As a result, it was concluded that a minimum loose curing period is necessary when granular quicklime is used.

Another phenomenon which became apparent was the forming of compaction planes within the specimens.

Photograph No. 2



Compaction Planes in Lime Treated Specimen

The compaction procedure provided that the soil sample be placed in the compaction mold in twenty equal increments. Compaction was taking place during this loading operation, with one stroke of the compactor being applied after the addition of each portion of material. The compaction mold revolves at a speed which allows six strokes of the compactor for each complete revolution. This increment loading and revolving mold creates a spiral effect in the compaction of the material as the depth increases. After completion of the compressive strength tests many of the test specimens were broken open for observation and, in several instances, a distinct stairstep effect was observed where the material separates on the smooth surfaces caused by the compactor foot. Photograph No. 2 offers an excellent illustration of this effect.

Because these compaction planes were caused by a single application of the compactor foot, it was assumed that normal compaction procedures during construction of a roadway would also create compaction planes when the treated material is placed in more than one layer.

Supplemental testing, following completion of the scheduled work, showed that specimen densities would have continued to increase with moisture contents up to 6 percent above the optimum established by Test Method No. Calif. 216. This is due to the lower effective compactive effort of the kneading compactor, as compared to the California impact test. However, it was found that the increased moisture contents made no substantial change in the relative stabilizing effects of the different limes. Treatment with the granular Quicklime C still resulted in higher densities and higher compressive strengths than the finer quicklimes and hydrated limes.

It is possible to establish moisture-density curves using the California kneading compactor. Since the kneading compactor may be used to produce specimen densities comparable to those achieved in the field, optimum moisture contents determined in this way should correlate more closely to construction moisture requirements.

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